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EFFECT ON VISION OF REPEATED EXPOSURE TO CARBON DIOXIDE

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Bureau of Medicine and Surgery, Navy Department

Research Work Unit MF12.524.004-9015D.01

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NAVAL SUBMARINE MEDICAL CENTER REPORT NO. 566

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SUMMARY PAGE

THE PROBLEM

To evaluate the effect on various visual functions of repeated exposure to low levels of carbon dioxide (CO_2).

FINDINGS

Breathing 1.5% of CO_2 in air resulted in some impairment in night vision sensitivity and in green color sensitivity. The impairment is associated with concentrations of CO_2 which have commonly been regarded as innocuous. All other visual functions remained normal.

APPLICATIONS

These findings are pertinent to submarine operations since submarine personnel may, through inadequate ventilation, pick up appreciable amounts of CO_2 in their blood. Results of this study may help provide a sound basis for the earliest possible detection of visual impairment as well as a possible means for its prevention.

ADMINSTRATIVE INFORMATION

This investigation was conducted as a part of Bureau of Medicine and Surgery Research Work Unit MF12.524.004-9015D—Vision Under Environmental Stress. The present report is No. 1 on this Work Unit. It was approved for publication on 14 February 1969 and designated as Submarine Medical Research Laboratory Report No. 566.

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ABSTRACT

The visual effects of repeated exposure to carbon dioxide (CO_2) at levels commonly regarded as innocuous were investigated. Exposure to CO_2 varied cyclically from .03 (air) to 3.0%, at one atmosphere pressure, every 24 hours for a period of six days. A battery of visual tests was administered during this period and in control periods both before and after the exposure to carbon dioxide. Among the various tests, night vision sensitivity and color sensitivity for green were the only ones which repeatedly detected impairment of efficiency during the period of exposure. All other visual functions remained normal.

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INTRODUCTION

A number of investigations[1-5] have been made of the effect of exposure to carbon dioxide (CO_2) on visual functions. These studies show, in general, increasing visual decrement with increasing percentages of CO_2 in the inspired air. There are, however, no comparable studies of the effect of repeated exposures to CO_2. This question is of practical importance for personnel aboard certain submarines. In these submarines the concentration of CO_2 rises steadily during the day; the atmosphere is then ventilated during the night, and the cycle repeats itself. Thus, submarines are never exposed to concentrations of CO_2 as great as have been investigated in some laboratory studies, but they are exposed to the lower concentrations repeatedly over a long period of time. In the present investigation, the question of the physiological effects of repeated exposure to CO_2, particularly as associated with simulated submarine conditions, has been examined.

This report deals only with the visual aspects of the general investigation.[6] Visual measurements during repeated exposure to CO_2 are significant, not only in terms of their direct and practical application to submarine service, but also may provide an index of physiological imbalance. The results of a series of tests dealing with the visual efficiency of one man under various conditions of CO_2 toxicity are presented. A variety of tests was used to simulate a wide range of the visual activities of submarine personnel. Further, the tests were selected to meet the following criteria: (1) they should be simple to administer, require little training, and produce reliable results; (2) there should be adequate standardization and comparative data obtained under a variety of controlled conditions; (3) they should provide as sensitive a measure as possible within the restrictions imposed by the first and second criteria.

EXPERIMENTAL PROCEDURE

All measures were carried out in a large pressure chamber where the temperature, ventilation, humidity, and the concentration of CO_2 could be maintained at any desired level; the total barometric pressure remained at one atmosphere (sea level).[6]

The subject (EK) was a 24 year-old medical student, who was thoroughly practiced in the experimental procedure. He was highly motivated, free of all ocular and physical defects, and in excellent physical condition.

After the subject entered the chamber, a three-day control series was conducted, during which time visual measurements in normal air were obtained. Having completed the observations with air, visual determinations were made with the subject variously exposed to CO_2 ranging from .03 per cent (normal air) to 3.0 per cent. Carbon dioxide was admitted to the chamber from cylinders outside the chamber at a rate selected to increase linearly the CO_2 content of the atmosphere to 3.0 per cent in 12 to 15 hours. The total duration of exposure to CO_2 was 15 hours per day for a period of 6 days. At the end of each 15 hour period, the chamber was opened and a fan turned on to blow out the high CO_2 mixture from the chamber. The subject was permitted to rest or sleep the remaining 9 hours of the 24.

Visual testing took place at three times during the day: 9:00 AM, 2:00 PM and 9:00 PM, when the CO_2 concentrations were .03, 1.5, and 3.0 per cent respectively. Certain tests were administered at 2:00 PM every other day; the rest of the battery was presented both at 9:00 AM and 9:00 PM on alternate days (see Table I).

In order to determine the reversibility of the changes produced by CO_2, a three-day recovery series in normal air was given. All details of the CO_2 experiment were simulated precisely except that the door of the chamber

Table I:—Summary of the experimental design

Days	Control		%	Exposure						Recovery	
Time	1	2	3 CO_2	4	5	6	7	8	9	10	11	12
9:00 AM	CT	O-R	.03	O-R	CT	O-R	CT	O-R	CT	O-R	O-R	CT
2:00 PM		NVT Monit. CM Duct. Accom.	1.50	NVT Monit. CM Duct. Accom.		NVT Monit. CM Duct. Accom.		NVT Monit. CM Duct. Accom.		NVT Monit. CM Duct. Accom.		NVT Monit. CM Duct. Accom.
9:00 PM		CT O-R	3.00	O-R	CT	O-R	CT	O-R	CT	O-R	CT	O-R

Legend: CT Color threshold
O-R Ortho-Rater
NVT Night Vision Test
CM Color memory
Monit. Monitoring
Duct. Duction
Accom. Accommodation

remained open and adequate ventilation was provided.

The following tests were employed:

1. **Visual acuity, lateral and vertical phoria, depth perception, and area of visual field.** These were measured with a Bausch & Lomb Master Ortho-Rater which permitted rapid testing under controlled conditions of target lighting and distance. Central visual acuity for distance (simulated distance of 26 ft.) and for near vision (13 inches) were measured for the right eye, left eye, and binocularly. The phorias were measured at the same distances. The horizontal limits of side vision of each eye was measured on a perimeter attachment to the Ortho-Rater. These tests were self-administered and recorded.

2. **Color sensitivity.** Two measures of color sensitivity were made. First, thresholds of color sensitivity were measured with a rotary color mixer. The color mixer was placed four feet from the chamber porthole; it was illuminated by a Macbeth daylight lamp and viewed against a dark surround. Gray paper was placed on the color mixer with either orange or green paper of the same brightness. The mixer was rotated at speeds above the critical flicker frequency and the subject was asked whether or not he could see any of the color in the gray. The proportion of colored and neutral papers on the rotor was varied in discrete steps; the 50 per cent threshold for color was obtained using the method of constant stimuli.

The second measure of color sensitivity consisted of a simple test of color memory. Seven familiar colored objects were selected; a plum, marischino cherry, tomato, green olive, lime, yellow mustard, and blue sky. A color series was formed for each object from Munsell papers; one of the colors matched the natural object and the others retained the same hue but were more or less saturated. Each series, consisting of four to six colors, was mounted on a 4"x6" white cardboard. The subject was asked to choose the most representative color for each object.

3. **Night vision sensitivity.** The Submarine Research Laboratory Night Vision Test[7] was administered to the subject in the darkened chamber after 15 minutes of dark adaptation. The test is composed of 120 small lights, presented at various positions throughout the subject's visual field, above, below, to the right, or to the left of a central fixation point. Two lights are presented on each trial and the subject is asked to report

their positions relative to the fixation. He is scored in terms of the total number of stimuli correctly identified.

4. **Amplitude of accommodation.** The amplitude of accommodation was measured for the right eye with a near point optometer. In this apparatus, the near point distances were obtained by having the subject move a test object (fine print) inward along the visual axis to the point where blurring began. The distance of the object from the spectacle plane was read off a rule graduated in diopters and age. Four such determinations were made per session.

5. **Duction.** Duction was measured using a pair of identical test-cards in a stereoscope, the Keystone Ophthalmic Telebinocular. The test-cards, placed apart at optical infinity and viewed with relaxed accommodation, normally are seen as fused in single vision. When measuring duction, the subject was asked to maintain single vision as long as possible while, at the same time he moved the cards toward each other. The point at which the single object became indistinct or blurred was the measure employed. Four such determinations of the blur point were made in each session and averaged.

6. **Monitoring.** In the monitoring task, the subject searched for the target, an intermediate-sized ring, among displays of 28 smaller and larger rings. Each display was presented automatically on a screen for 4.5 seconds by a Kodak Carousel slide projector. The target occurred 72 times at random intervals over 480 displays. Each display was followed by 4.5 seconds of darkness during which time the subject responded by pressing one of two buttons, for 'yes' or 'no'. The responses were recorded automatically by a pen and moving paper system. The subject viewed the displays through the porthole. The total amount of time spent in each monitoring session was 36 minutes.

RESULTS

A. The effects of breathing normal air versus 3.0 per cent CO_2

Ortho-Rater experiments: The results obtained in normal air and 3 per cent CO_2 are shown in Table II. Each datum represents the mean of from two to four day's measurements.

Table II:—Mean Ortho-Rater performance for subject EK in normal air and 3 per cent CO_2 in air

Time	Visual Acuity (reciprocal min.)		Phorias Vertical				Phorias Lateral		Visual Field		Depth
	Near	Far	Near		Far		Near	Far	Right	Left	(% change)
Control (air)	1.7	1.7	1.25	LH	.50	LH	0.0△	+2.0△	93.5°	98.0°	
Exposure											
AM (air)	1.6	1.7	1.00	LH	.25	LH	−0.5△	+0.5△	90.0°	95.0°	0.0
PM (CO_2)	1.7	1.7	1.00	LH	.40	LH	−0.5△	+1.3△	93.3°	95.0°	0.0
Recovery (air)	1.7	1.7	1.00	LH	.25	LH	+0.2△	+1.2△	93.3°	96.6°	0.0

Inhalation of CO_2 caused no noticeable change in visual acuity, the heterophorias, depth perception, or area of visual field. Likewise no consistent alterations were found in the post-exposure control period.

Color thresholds: The average thresholds for both orange and green under the various conditions are shown in Fig. 1. A comparison of the green thresholds during the exposure period with thresholds during control and recovery periods reveals poorer sensitivity under the CO_2 condition. Furthermore, the daily thresholds, without exception, showed a rise from morning to evening as the CO_2 level changed from .03 to 3.0 per cent. The thresholds for orange, while somewhat similar in overall form, did not show the same clearcut differences.

B. The effects of breathing 1.5% CO_2

Amplitude of accommodation and ductions: The mean results, based upon from 8 to 16 measurements are shown in Table III. In general, the capacity to accommodate was not altered during exposure to CO_2 or during subsequent recovery.

Color memory: No consistent alterations in performance after exposure to CO_2 were revealed by this test.

Night vision sensitivity: Daily scores, in terms of the total number correctly identified, are shown in Fig. 3. There was evidence of a decrease in sensitivity under CO_2 and an apparent reversal of this trend during the last day of recovery.

Table III:—Mean amplitude of accommodation and duction at .03 (air) and 1.5 per cent CO_2

Time	Accommodation (diopters)	Age (years)	Duction (prism diopters)
Control (air)	8.0	33.0	13.7 base out
Exposure (CO_2)	8.1	32.5	9.6 base out
Recovery (air)	7.8	33.7	10.3 base out

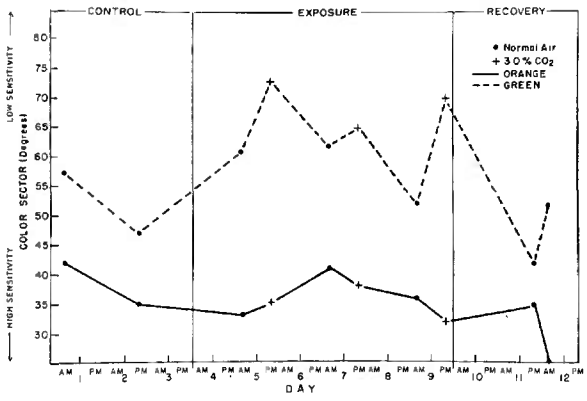

Fig. 1. Changes in the color sensitivity of Subject EK breathing normal air and a 3 per cent CO_2 mixture at 1 atmospheres pressure.

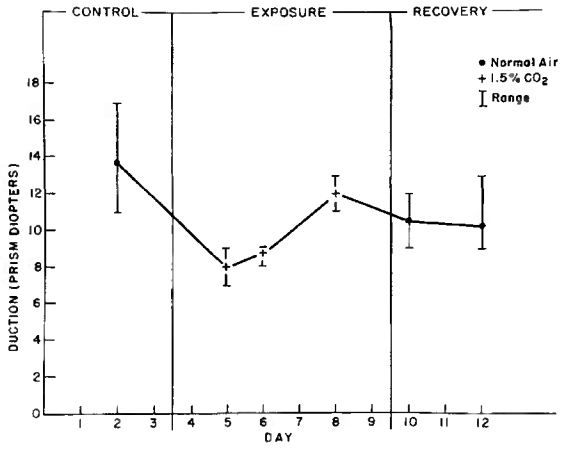

Fig. 2. Changes in duction for Subject EK breathing normal air and 1.5 per cent CO_2 mixture.

The results of the duction test are not completely clear. There is some indication of a loss in the power to maintain single vision during the first two days of exposure to CO_2 (Fig. 2), but there appears to have been a recovery on the third day of exposure, to the control level. It should be noted that the subject sometimes reported great difficulty in making these determinations.

Monitoring: Figure 4 shows the percentage of signals detected under the various conditions of the experiment. The percentage of detection responses made by the subject when, in fact, no signals were present is

shown in the inset of Fig. 4. There was a progressive increase in the number of correct detections, reaching a peak value in the last determination. This improvement was significant beyond the .01 level. Of interest is the fact that the "false alarm" responses were in no way correlated with detection performance.

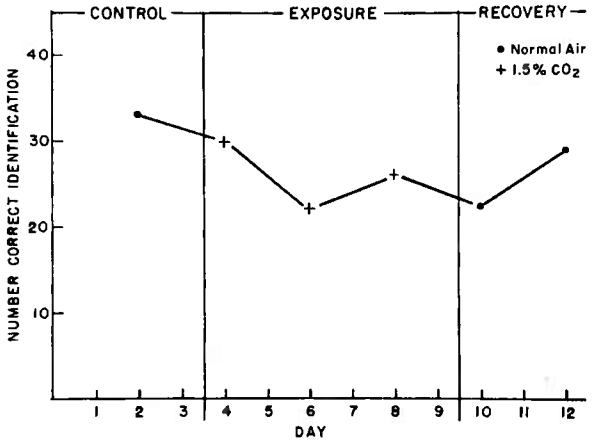

Fig. 3. Changes in the night vision sensitivity of Subject EK breathing normal air and 1.5 per cent CO_2 mixture at 1 atmospheres pressure.

In order to evaluate this trend, a subsequent control experiment in air was performed with a 22 year-old female graduate student (SD). All details of the procedure were simulated precisely except that normal air was used throughout. The results are also shown in Fig. 4. The shape and slope of the performance curves for the two subjects were very similar; only the mean level of performance differed. Thus, the level of monitoring performance seems to be directly related to a learning effect. It is of particular interest that the learning effect should occur in the performance of subject EK throughout the exposure period.

Another type of analysis is a portrayal of performance during the monitoring period. In general, such analysis reveals three stages that characterize learning curves during continuous performance: the warm up jump from the first to the second or third group of trials of each day's performance, a leveling off representing maximum performance, and a gradual decline during further continuous practice. Fig. 5 shows three such daily curves, that is, the percentage of correct detections in successive 6-minute intervals, averaged over days. The performance curve of EK under CO_2 does not reveal the typical warm up and decrement effects, while under normal air, it does.

DISCUSSION

While there seem to be no other studies directly comparable to our own on the visual effects of chronic intermittent exposure to CO_2, it should be noted that several investigators have found evidence of visual impairment associated with acute exposure to CO_2 inhalation. Observations by Alpern and Hendley[1] on the effects of respiratory acidosis (induced by breathing a mixture of seven per cent CO_2 and 93 per cent O_2) on the

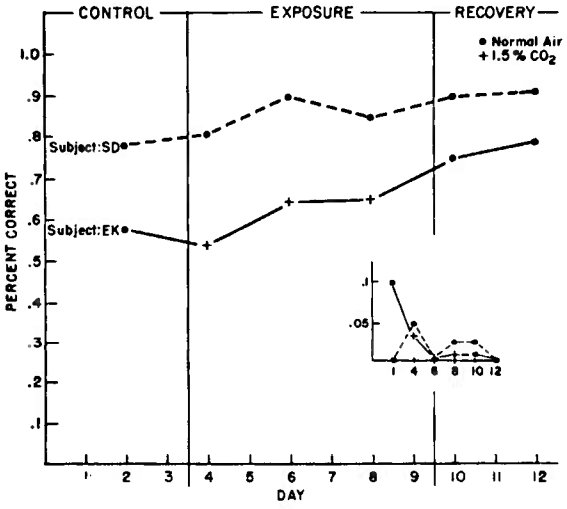

Fig. 4. Changes in the monitoring performances of Subject SD breathing air, and Subject EK breathing air and a 1.5 per cent CO_2 mixture at 1 atmospheres pressure. The inset shows the per cent false detections against days of testing.

critical flicker fusion (cff) suggest that an increase in CO_2 tension causes a decrease in cff. Wald et al.,[2] studied the absolute visual threshold and found noticeable deterioration of this function when the CO_2 content in air

was raised to five per cent. Schaefer and Carey[5] showed significant changes in flicker fusion frequency and in latency of alpha blocking at concentrations of three per cent. On the other hand, no decrements in sensory functioning were found as a result of prolonged exposure to 1.5 per cent of CO_2.[4] In general, reliable amounts of impairment have been found only when the percentages of CO_2 in air were 3 to 5 per cent or greater.

Of the various visual tests employed in the present investigation, scotopic sensitivity and color sensitivity (for green) were the only ones which seemed to produce evidence of impaired efficiency at CO_2 concentrations as low as 1.5 per cent in air. The impairment

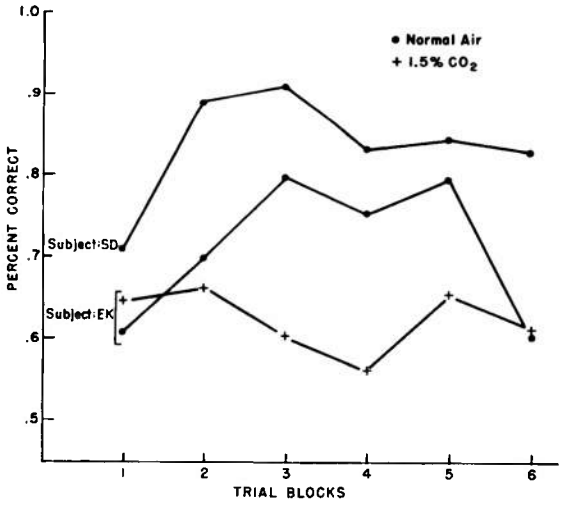

Fig. 5. The effect of breathing normal air and a 1.5 percent CO_2 mixture on the relation between monitoring performance and trials of each day's performance. The points represent the mean of 3 days' data obtained in air or when breathing CO_2.

revealed by these tests is associated with repeated exposure to degrees of CO_2 toxicity that have otherwise been regarded as innocuous. One possible reason for the difference is that the test battery selected for this study included some extremely sensitive visual measures. It may be that the failure to find decrements previously resulted simply from the use of fairly gross measuring devices. On the other hand, the results could indicate a cumulative effect from repeated exposure to three per cent CO_2; this serious possibility deserves further investigation.

The degree to which the present findings hold for other individuals, remains to be determined, of course. Nevertheless, the importance of guarding against the accumulation of CO_2 in submarines and of its adequate removal is emphasized. With the increasing complexity of submarines, many critical visual discriminations have to be carried out where clear vision is required. It is precisely for this reason that the need for further investigations becomes obvious, to elucidate the nature of these impairments and the mechanisms underlying them.

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13. ABSTRACT

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